Chapter 7

Relevance of ATF/ATF2

7.1 Facility purpose

The main objective of the Accelerator Test Facility (ATF) built at the High Energy Accelerator Research Organization (KEK) in Tsukuba, Japan, is to serve as R&D platform for the requirements of linear accelerators, in particular ILC. ATF obtained the record of minimum vertical beam emittance [25, 26], leading to the next step, the vertical beam size reduction at the IP.

The Final Focus Test Beam (FFTB) [27], at the Stanford Linear Accelerator Center (SLAC) in the U.S.A., explored the beam size reduction using the non-local chromaticity correction scheme. It operated since 1994 to 1997 with a final result of 70nm in the vertical plane. The designed 40nm was not achieved and the difference was attributed to beam jitter and tuning limitations [28].

The beam size reduction using the local chromaticity correction is explored by an extension of the original design, called ATF2 [29, 30], then ILC-like FFS lattice scaled down to 100m with two goals: (**goal 1**) achieve 37nm of vertical beamsize at the IP and (**goal 2**) the stabilization of the IP beam position at the level of few nanometres.

The CLIC, ILC and ATF2 main parameters are shown in Table 7.1, where the vertical cromaticity ξ_y is similar for ATF and ILC designs. The ILC and ATF2 relative increment in beam size is a factor 10, calculated from L^*, β^* and σ_δ, if chromaticity is not corrected.

Parameter	Symbol	Units	CLIC 3 TeV	CLIC 500 GeV	ILC	ATF2
Beam Energy per beam	E	GeV	3000	250	250	1.3
Energy Spread (e^+/e^-)	σ_δ	%	0.3	0.3	0.07/0.12	0.06∼0.08
Final quad to IP distance	L^*	m	3.5	4.3	3.5/4.5†	1.0
Horizontal β function at the IP	β_x^*	mm	6.9	9	11	4
Vertical β function at the IP	β_y^*	mm	0.07	0.2	0.48	0.1
Normalized horizontal emittance	ϵ_{xN}^*	μm	660	2400	10	2.8
Normalized vertical emittance	ϵ_{yN}^*	nm	20	25	35	31
Horizontal beam size	σ_y^*	nm	45	200	5.9	37
Vertical beam size	σ_y^*	nm	0.9	2.3	5.9	37
Natural vertical chromaticity	ξ_y		50000	43000	7300/9400†	10000

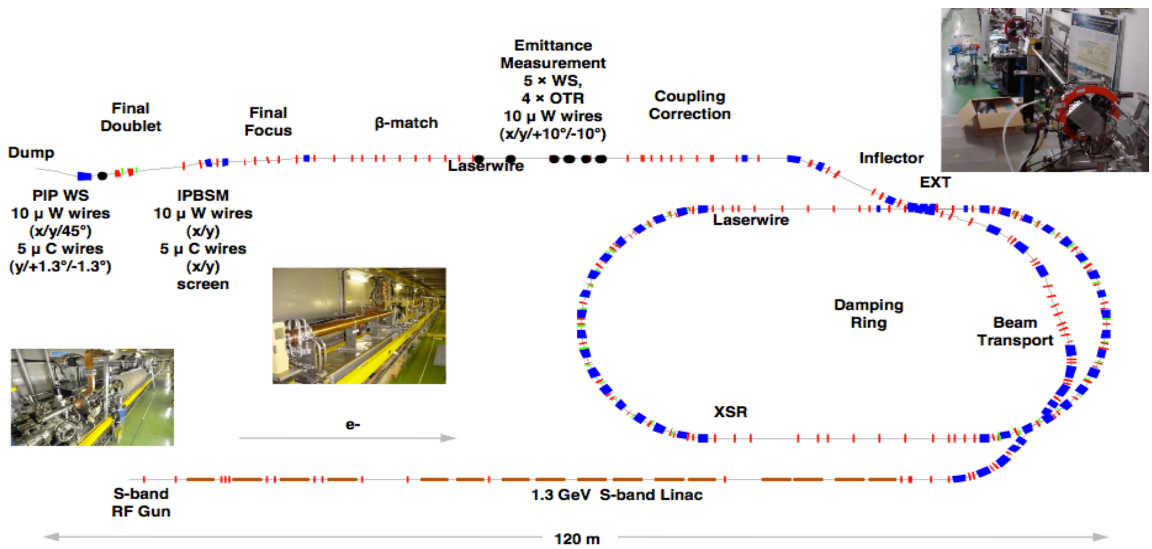
Table 7.1 – Design parameters of ILC and ATF2 Final Focus. †The ILC lattice has two detector options: SiD and ILD.

When compared with the current linear accelerator projects, ATF2 will not be as sensible to time variations due to ground motion and wakefiels because of the shorter linac, nor the misalignments because the ATF2 FFS in an order of magnitud shorter than in ILC. However the tolerances of magnetic fields, jitter vibration and power supply stability are similar in ATF2 and ILC.

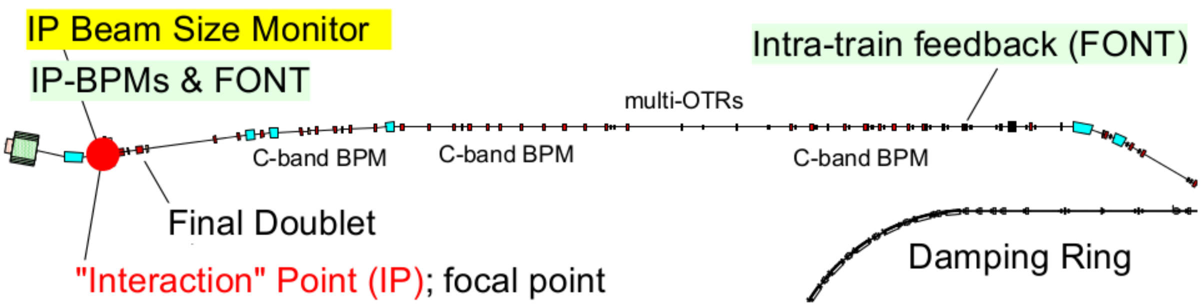
On the other side, ATF2 needs dedicated systems to measure the beam position and beam size at the IP because the principles of beam-beam interaction used in a collider are not applicable.

7.2 Beam line Description

The ATF accelerator facility, shown in Fig. 7.1, is composed by a photocathode giving electrons to a linac which accelerates the particles to 1.3 GeV, a damping ring to reduce the beam vertical and horizontal emittance and an extraction line which provides bunch packets to the Final Focus Section (FFS) where the beam is transported to the nominal IP and dump. The goal is to generate, accelerate and damp a train of 20 bunches with 2×10^{10} particles per bunch and 2.8 ns bunch spacing. This is a description extracted from [29, 31, 32].



(a) Disposition of the Accelerator Test Facility (ATF), composed by a photocathode, a linac to 1.3GeV, a damping ring, an extraction line, the Final Focus (FF), and the beam dump.



(b) Zoom over the extraction line, and Final Focus Section, highlighting the nominal Interaction Point location (IP). This region is known as ATF2.

Figure 7.1 – Diagrams containing the ATF composition and a zoom on the ATF2 section.

7.2.1 The RF Gun and Linac

The total length of the linac is 80 m divided in: 18 m for the pre-injector section and 70 m long accelerator section with energy compensation structures and 12 m for the transport line to the damping ring (DR) and a positron test stand. The RF gun with a 1.6 cell S-Band Cs_2Te photocathode generates an electron beam with intensity up to 3.2nC per bunch. The pre-injector contains also an accelerating structure. An accelerating field of 35.2 MeV/m is required to accelerate 20 bunches of 2×10^{10} particles per bunch. The linac is operated at a repetition rate of 25 pps (pulses per second) to allow circulating 5 bunch trains in the Damping ring. Table 7.2 shows the main parameters of the DR.

Beam energy, E_{beam}	1.54 GeV
Bunch population, N	2×10^{10}
Bunches per train, N_b	20
Bunch spacing, Δt_{bunch}	2.8 ns
Energy spread Full Width, σ_δ	<1.0% (90% beam)
Normalized emittance, $\epsilon_{Nx/y}$	$< 3 \times 10^{-4}$ m·rad

Table 7.2 – Basic design parameters of the ATF injector linac.

7.2.2 The Damping Ring

The ring has a length of 138.6 m. It has achieved in 2004 a vertical normalized emittance of 1.5×10^{-8} m·rad, equivalent to 6pm·rad for a bunch intensity of 10^{10} particles. It was achieved by a precise alignment of components and beam control. The value of the horizontal emittance is determined by the structure unit cell. The ATF DR consists in 36 of these units cells and the main parameters are in Table 7.3.

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Bunch spacing, Δt_{bunch}	2.8 ns
Energy spread Full Width, σ_δ	<1.0% (90% beam)
Normalized emittance, $\epsilon_{Nx/y}$	$3 \times 10^{-6}/3 \times 10^{-8}$ m·rad

Table 7.3 – ATF DR main parameters.

7.2.3 The extraction line

In the extraction line the beam is extracted from the DR by means of a first kicker (KICKER1), and then passe off-axis through some magnets centered on the DR reference orbit. Then, the beam passes through three septum magnets which complete the extraction. After the extraction, the beam passes through a dispersion supressor section, with a second kicker mirroring the extraction one (KICKER2) in order to reduce fluctuations.

There are two extraction modes: single bunch and multibunch.

In single bunch mode one bunch is extracted approximately every 1/3 s from the damping ring to the ATF2 line. In multibunch mode a train of up to 20 bunches is extracted from the damping ring. The number of bunches and spacing is set by the damping ring fill up.

7.2.4 The extraction diagnostic section

After the extraction, the diagnostic section is used for measuring the emittance and correcting betatron coupling. This section has been designed to be as close as possible to the ideal skew correction described in [33].

The measured vertical emittance in a diagnostic region downstream shows a factor 3 of increase and dependence with beam intensity. One of the possibilities of the emittance growth is the non-linearity of the magnetic fields in the extraction region experienced by the beam when passing off-axis. One second possibility is the wakefields induced by the extraction kicker. The correlation with beam intensity could be due to the beam position monitors response.

7.2.5 The ATF2 lattice

The ATF2 lattice could be subdivided in two sections : the matching section and the FFS. The following section describes the FFS.

The FFS focuses the beam to an small vertical beam size following the telescope design with local chromaticity correction, as in Sect. 4.2. The top of Fig. 7.2 shows the lattice elements and the optics functions along the FFS. The Final Doublet (FD), QD0FF and QF1FF, provide the vertical and horizontal focusing respectively. The horizontal off-momentum function η and the pair of sextupoles in the FD is used to cancel the beam size dependence on energy spread at the IP.

The second pair of sextupoles in the lattice section from 70 to 75 m are used to cancel the geometrical components induced by the sextupoles in the FD. And, adittional chromaticity is created upstream QF7 to match the local correction [8].

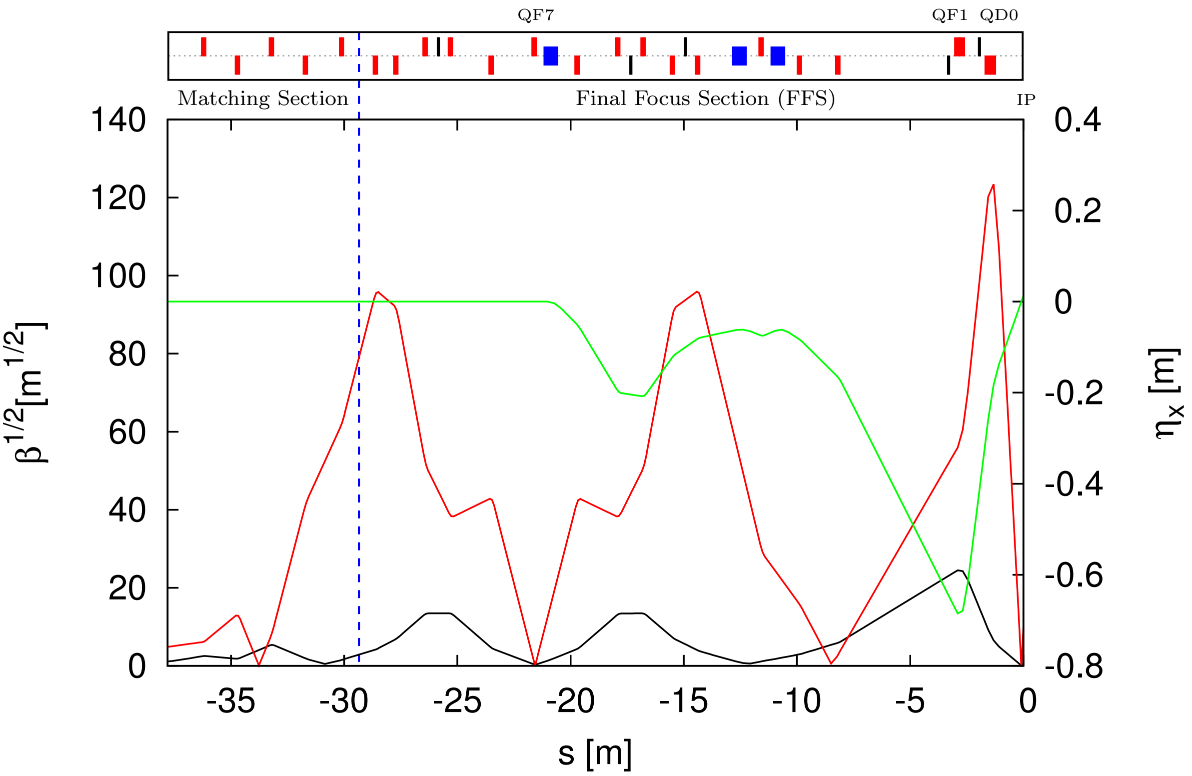


Figure 7.2 – Optical functions in the Final Focus Section at ATF2. On top is the ATF2 lattice: dipoles in blue, quadrupoles in red and sextupoles in black.

Quadrupoles displacement steers the beam, while sextupoles displacement induce focusing. This have an impact on the beam size. The tolerances to misalignments, roll angle and magnet strength errors in the FFS have been initially studied with a target of 2% impact in the beam size, and it has shown similar tolerances results to those of ILC [32]. Magnets are placed on individual movers to allow the beam steering and adjustment of relative alignment in X, Y and Roll angle.

7.2.6 The IP Region

The β functions at the IP, β^*, can be set by changing the matching section magnets strength. Three configurations are normally used : 1BX1BY, 10BX1BY, and 100BX1000BY, where the factor indicates the number of times that the original β^* has been amplified.

The 1BX1BY optics has the original design parameters. Here the angular divergence of the beam is 0.35 mrad vertically and 0.52 mrad horizontally in the IP region.

The 10BX1BY preserves the β_y^* goal while relaxing the tolerance to multipole errors in magnets by increasing ten times the original β_x^*, making them comparable with those of ILC 500 GeV [34]. This optics is the one shown in Fig. (7.2) and it is currently used in operation.

The 100BX1000BY optics sets a parallel beam through the IP area by enlarging the beam size at the IP. It is principally used to avoid the issues of large angle divergence displayed by the 1BX1BY optics.

Even smaller β_y^* functions have been explored recently at ATF2 aiming to estimate lower β^* tunability and beam size measurements limitations [35].

Figure (7.3) shows the beam size in vertical and horizontal plane for several optics combinations in a region of 300 mm around the IP. It also shows clearly how the beam divergence affects the beam size along the IP region.

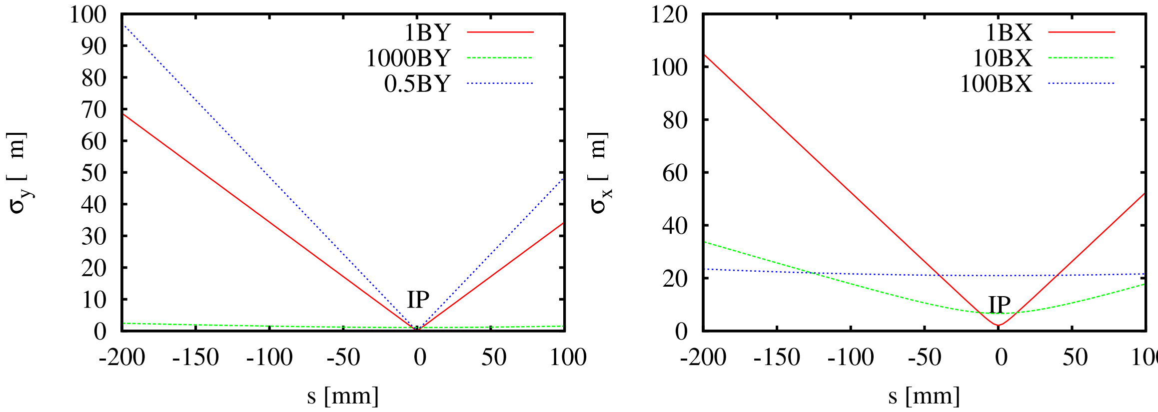
QD0 strength sets the vertical beam waist location with an small impact on the horizontal beam waist location, while QF1 does the opposite. The two are set to put the beam waist to its the nominal location at $s = 0$. However, one or a combination of the two quadrupole strengths can be used to bring the beam waist to any location upstream or downstream. Moving the beam waist along the section of the IP region used to draw Fig. 7.3 is effectively changing the focal distance by less than -20% to +10%.

QD0 and QF1 horizontal and vertical movers can also be used to steer the beam in the FD region, changing the position and angle through the IP region. Angle can also be steered by moving QF7 horizontally and vertically because of its location on a focal point upstream. See Fig. 7.1b showing the QF7 location and Eq. (4.2) to see that the kick at the input of a telescope lattice affects only the angle at the output.

7.3 Beam Size Measurement at the IP

A direct beam size measurement at the ATF2 IP is required because it can not be deduced from beam-beam interaction as in a collider.

The Beam Size Monitor (IPBSM) measures the number of scattered photons from an electron-photon collission between the particle bunch and a perpendicular interference pattern generated by high intensity laser perpendicular to the bunch trajectory [36]. The number of photons is proportional to the photon density at the beam position. Moving the beam or



(a) Vertical beam size near the IP. (b) Horizontal beam size near the IP.

Figure 7.3 – Vertical and horizontal beam sizes for 1BY, 1000BY, and 0.5BY in the vertical plane, and 1BX, 10BX and 100BX in the horizontal plane.

scanning the phase of the laser fringe produces a modulation of gamma flux ray depending on beam size [32]. Figure 7.4 shows an schematic design of the IPBSM.

It was previously used at the FFTB line at SLAC [37] and now it is located in the IP region at ATF2 [38].

At ATF2, it is installed in a vertical optical table where the laser incident angle can be adjusted to change the interference fringe size measuring beam sizes from 6 μm down to 25 nm. Figure 7.5 shows the beam path along the vertical optical table for three angles modes and the correspoding range of beam measurements.

Larger beam sizes are measured by a wire scanner installed in the same region. It consists in a wire moved across the beam generating bremstrahlung gamma rays. The number of photons is proportional to the charge of the slice interacting with the wire at each position setting. Profile is constructed from the number of photons as a function of wire position [39].

7.4 Beam stabilization

Three regimes are defined for the beam stability: fluctuations in timescales that are effectively uncorrectable (jitter), fast fluctuations that can be corrected by feedback (FB) systems, and slow or static fluctuations that can be addressed by systematic orbit correction (tuning).

The jitter requirement for goal 1 is beam jitter less than 30% of σ_y, while goal 2 requires jitter less than 5% of σ_y. The measured bunch position jitter upstream the FD for single bunch extraction mode, i.e. the fluctuations on bunch position before the strong focusing magnets, is around 10∼20% of beam size on the vertical plane and 5∼10% on the horizontal plane [40]. Additional jitter could come from the FD.

7.4.1 Tuning

The contribution to beam size due to field errors is considered static or slowly changing. It is possible to reduce their impact by systematic orbit correction using magnetic or mechanical means [29]. Goal 1 jitter requirements can be achieved for single bunch extraction.

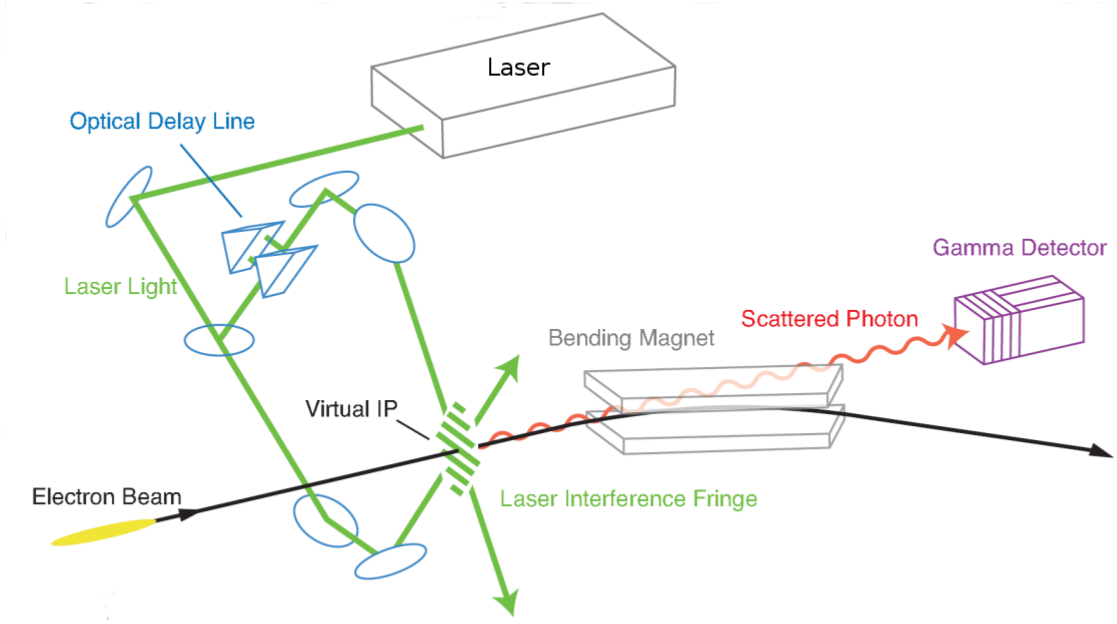


Figure 7.4 – IPBSM schematic design. The particle beams crosses the interference pattern generated by a perpendicular beam. The number of electron-photon interactions varies with the fringe size and the particle beam size.

7.4.2 Feedback

The fluctuations comming from ground motion, magnet strength fluctuations, changes in the damping ring, energy oscillations are considered fast errors. Aso, the pulse to pulse bunch jitter from multibunch extraction requires active correction.

The feedback system is then the last line of defense to correct the beam trajectory and three schemes are tested in ATF2 using two bunches.

- Upstream FB: Measures the first bunch position in the IP region and uses a set of kicker upstream the matching section to stabilize the position of a second.
- Feedforward: Measures the first bunch position upstream the matching section and uses

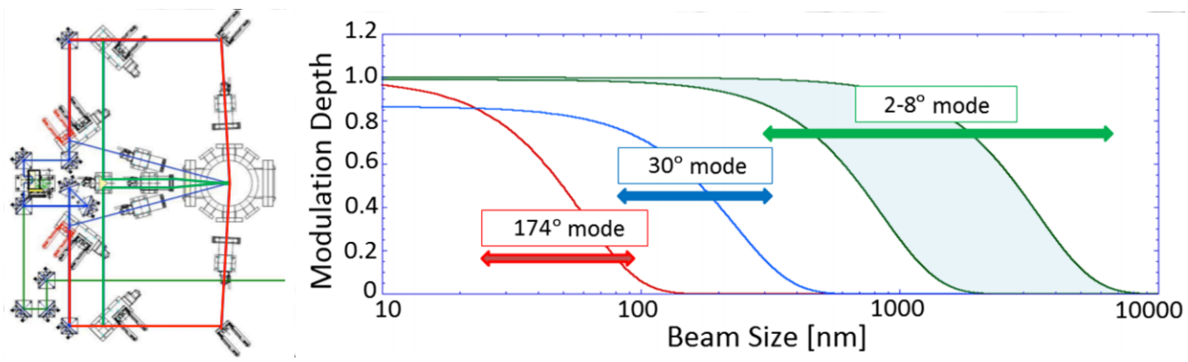


Figure 7.5 – (Right) IPBSM laser path over the optical table perpendicular to the beam propagation. (Left) Beam size resolution for the angle modes : $2 \sim 8\,^{\circ}$ in green, $30\,^{\circ}$ in blue and $174\,^{\circ}$ in red.

a kicker in the IP region to stabilize the position of a second.

- Local IP FB: Measures the first bunch position in the IP region and uses a kicker in the IP region to stabilize the position of a second.

7.5 Recent achievements and current work

In 2014 vertical beam size about 55nm was observed at ATF2 [41], and since then smaller beam size can be achieved systematically down to 44nm [42] demonstrating the local chromaticity correction method at charges below 0.1×10^{10} particules per bunch.

The identified issue of intensity dependence is currently explored by the ATF2 collaboration. However, at low intensities the beam size remains above the designed 37nm. Possible contributions are: (1) the increase of the incoming beam emittance through out the ATF2 line, (2) systematic errors and resolution limitations on the beam size monitor, (3) beam drift beyond the tolerable margin and (4) undetected optics mismatch.

Last two issues can be adressed by measuring the beam trajectory in the IP Region after the Final Doublet. In adittion, looking forward to **goal 2**, beam position measurement is a requirement for beam stabilization.

The work here described corresponds to the beam position monitors installed in 2013 by LAL in collaboration with Kyungpook National University (KNU), the Feedback in Nanosecond Timescale (FONT) group from Oxford, and the ATF2 staff.

7.6 Position Measurement Requirements

A direct beam position measurement at the ATF2 IP is required because it can not be deduced from beam-beam deflection due to offsets as in a collider [43].

Knowing the beam trajectory with nanometric precision is valuable information for beam tuning and requirement for feedback. The position measurement system could be used to correct the beam positions used in the reconstruction of the IPBSM modulation pattern, in order to remove the dilution from beam jitter in the beam size reconstruction pulse by pulse.

Therefore, a set of three cavities (IPA, IPB and IPC), two upstream and one downstream of the nominal IP, were installed and are used to measure the beam trajectory in the IP region thus providing enough information to reconstruct the bunch position and angle at the IP.

Cavities are located at $s = -167.9$ mm, $s = -87.1$ mm and $s = 87.1$ mm, with respect to the nominal IP at $s = 0$. It has been shown in section 7.2.6 the effect of different optics on the beam size along the IP region. As the measured beam jitter upstream is around $10 \sim 20\%$ of beam size, then, the change of optics will have a direct impact on the dynamic range of the position measurement.

Dynamic Range

Table 7.4 shows that beam size only increases by a factor two among the cavities using the 1000BY optics, while Table 7.5 shows a beam one and two thousand times larger than the beam size at the focal point.

From these optics settings the maximum vertical beam size is 58 μm. The dynamic range required for the cavity is then around 10 to 11 μm using the 20% jitter to beam size ratio.

	IPA	IPB	IP	IPC
s [mm]	-174.2	-87.1	0	87.1
σ_y [1.086μm]	2.0	1.3	1	1.3
$\sigma_{y'}$[0.011mrad]	0.5	0.8	1	0.8

Table 7.4 – Vertical beam size at the cavities positions and the IP with the 1000BY optics.

	IPA	IPB	IP	IPC
s [mm]	-174.2	-87.1	0	87.1
σ_y [34 nm]	1.7×10^3	871	1	871
$\sigma_{y'}$ [0.3 mrad]	$0.6(10^{-3})$	$1.2(10^{-3})$	1	$1.2(10^{-3})$

Table 7.5 – Vertical beam size at the cavities positions and the IP with the 1BY optics.

Resolution and Calibration

The beam stabilization to the nanometer level requires position measurement with nanometric resolution. In addition, due to the low β^* for the nominal 1BX1BY optics, the beam size and therefore the jitter increases rapidly making the 1 nm resolution over the 10 μm dynamic range a challenge. The calibrations must be then valid for measurement over 3 to 4 order of magnitud.